Solar Spectroscopy and Diagnostics

Solar spectroscopy and diagnostics provide the opportunity for determining the physical parameters in different parts of the solar atmosphere.

The story of solar spectroscopy really began in 1666, when Isaac NEWTON studied the *phenomenon of colors* using a triangular glass prism which he bought in a local market. In his early experiments, he split sunlight into the colors of the rainbow. The radiation from the photosphere is similar to that of a black body with a characteristic temperature of 6000 K, which peaks in the visible wavelength range. It was only much later, in 1814, when FRAUNHOFER determined that the hundreds of dark lines in the solar visible spectrum were actually a property of the sunlight, rather than any earthly phenomenon (see FRAUNHOFER LINES). During a total eclipse of the Sun, the Fraunhofer spectrum, normally seen as absorption lines, is briefly replaced by an emission-line or flash spectrum from the chromosphere, the thin layer just above the photosphere.

QUANTUM THEORY, developed in the 1920s and 1930s, provided an explanation for spectral emission and absorption lines in terms of changes of energy state of atoms by discrete amounts—*quanta*, related to the wavelength of the radiation. Each atom has characteristic *fingerprints* of spectral lines which enable us to dissect the spectrum and determine the nature of the solar plasma where it originated. A plasma is a gas in which the atoms have been ionized.

At the time of totality, the CORONA is visible in all its glory—the *crown* around the Sun. Normally, the visible emission from the corona cannot be seen, since it is very weak, only a millionth of the intensity of the SOLAR PHOTOSPHERE or surface of the Sun. During an eclipse, the Moon blocks out exactly the photosphere and allows us a brief glance at the corona. Skilled work by a gifted French astronomer called LYOT, provided in 1930 an instrument, a coronagraph, which could simulate a total eclipse, allowing the visible coronal spectrum to be continuously observed. The coronal visible spectrum comprises emission lines (the brightest are the coronal green, red and yellow lines). These lines provided an intriguing puzzle for many years, indeed, a new element called *coronium* was invented to explain them. Although Lyot noted that the width of the green line indicated a characteristic temperature much higher than the photosphere, it was the painstaking scientific investigations by Grotian and Edlen around 1940 which eventually led to the identification of these lines from ions which only exist at very high temperatures (above 10^6 K). The green line comes from Fe XIV (iron with 13 electrons stripped off), the red line from Fe X and the hottest line, the yellow line, is from Ca XV. Thus it was established that the corona is very much hotter than the photosphere—a fascinating phenomenon, which solar physicists are still seeking to explain.

Modern technology has enabled us to move far beyond the visible wavelength range into the ultraviolet, x-rays, infrared and radio wavelength ranges. From space observatories, we are able to monitor the corona continuously in the UV and x-rays. At these wavelengths we see hundreds of emission lines, covering a wide range of temperatures. Spectroscopic diagnostics encompasses the study of techniques which have been developed to deduce plasma parameters, such as electron density and temperature, elemental abundances and mass motions from spectral lines. A comprehensive review of spectroscopic diagnostics for solar and stellar plasmas in the VUV (100–2000 Å) was published by Mason and Monsignori Fossi (1994). To use these techniques it is necessary to build accurate atomic models, including all the important processes and using the best available atomic data.

Electron temperature

As the temperature increases in a gas, the particles become very energetic, so more and more electrons get stripped off the ions. For example, neutral oxygen has eight electrons, but at a temperature of 10^5 K, four electrons have been removed. The ion formed is O V (or O^{4+} in notation used by atomic physicists). So, if we make images of the solar atmosphere in different spectral lines, we are in fact able to take 'slices' at different temperatures. For example, the Coronal Diagnostic Spectrometer (CDS) on the Solar and Heliospheric Observatory (SOHO) was designed to do just that. Simultaneous rasters, up to $4' \times 4'$ in size, can be obtained at different wavelengths, with a high spatial resolution (approximately 3″) (see figure 1). The SOHO-CDS instrument covers lines from ions formed over a wide temperature range (2×10^4–6×10^6 K), including the low-temperature emission from He I at 584 Å (2×10^4 K), transition region emission from O V 630 Å (2.5×10^5 K); the Mg IX 368 Å line at coronal temperatures (10^6 K) and the Fe XVI 335 and 361 Å lines observed in active regions (2×10^6 K). From the CDS rasters it is evident how different the solar atmosphere looks at various temperatures.

During solar flares, the temperature can exceed 10^7 K, and many lines from highly ionized iron ions can be observed in the x-ray wavelength range. Figure 2 is an observation made with the Bent Crystal Spectrometer (BCS) instrument on the YOHKOH satellite (ISAS, Japan). The presence of the Fe XXVI lines indicates a very high temperature of around 30×10^6 K.

In the simplest coronal model approximation, we find that the emission line intensity from a volume of plasma V can be expressed as

$$I(\lambda_{ij}) = \frac{1}{4\pi} Ab(X) \int_V G(T) N_e^2 \, \mathrm{d}V (\text{photons s}^{-1}\,\text{sr}^{-1})$$

where λ_{ij} is the wavelength for the transition between energy level j and i in the ion, $Ab(X)$ is the element abundance and N_e is the electron number density (cm^{-3}). The *contribution function*, $G(T)$, contains all of the relevant atomic physics parameters—it is strongly peaked in temperature (see figure 3).

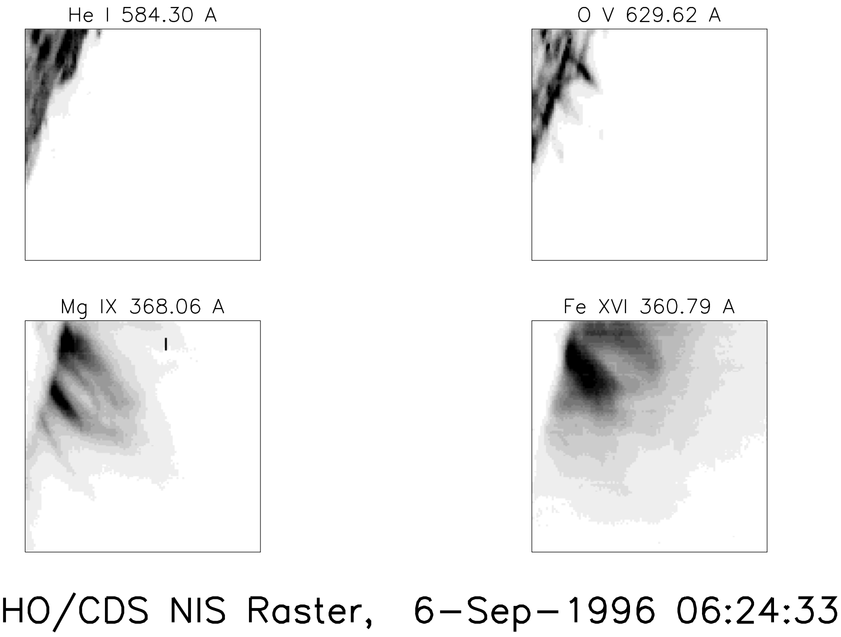

Figure 1. SOHO-CDS rasters of an active region, showing emission from He I, O V, Mg IX and Fe XVI.

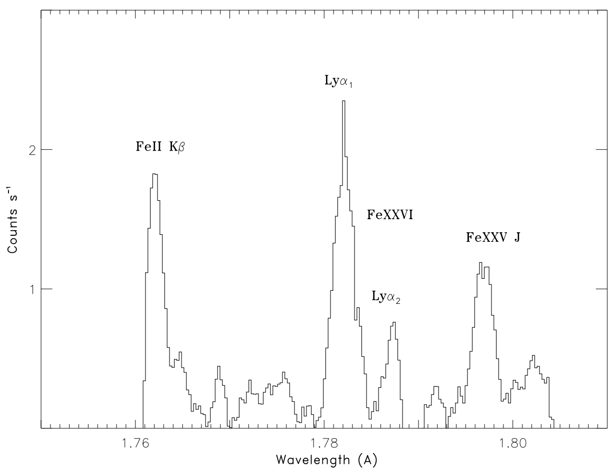

Figure 2. Fe XXVI lines observed with the YOHKOH BCS instrument. (Courtesy of Pike.)

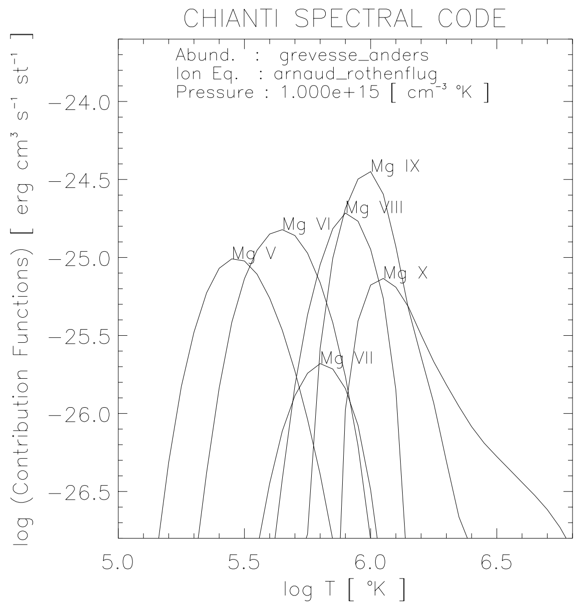

Figure 3. The contribution functions $(G(T)Ab(X)/4\pi)$ for various ionization stages of Mg: Mg V (353.09 Å), Mg VI (349.17 Å multiplet), Mg VII (363.77 Å), Mg VIII (315.04 Å), Mg IX (368.07 Å), Mg X (624.94 Å).

From a study of the intensity of spectral lines formed at different temperatures, it is possible to deduce the amount of material in each temperature range, which is called the *emission measure distribution*. With further assumptions about the geometry of the region, one can directly compare the observations with theoretical models.

Vast quantities of atomic data are required to simulate the observed spectra. For example, the CHIANTI atomic database and analysis software (Dere *et al* 1997), has been developed as a collaboration between the USA, Italy and the UK to provide a comprehensive dataset for ions of astrophysical interest. A comparison of the simulated and observed CDS spectrum is given in figure 4. Several other atomic databases and packages are available such as the Atomic Data and Analysis Structure (ADAS) developed at Strathclyde University.

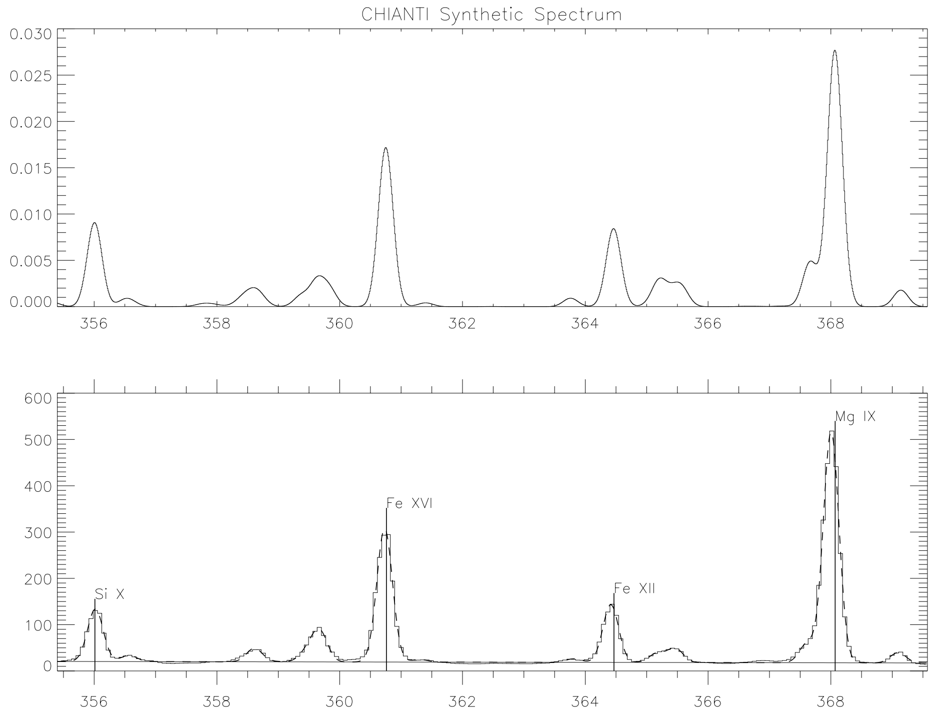

Figure 4. A sample CDS-NIS active region spectrum (355–370 Å) is shown in the lower plot—the dashed curve is a multi-Gaussian fit with background. The upper plot is a standard active region spectrum from CHIANTI.

Electron density

The electron pressure is an important parameter in any theoretical model for the plasma. This is proportional to the product of the electron density and temperature. Experience from solar observations is that the plasma often exists in the form of unresolved filamentary structures, even down to the best spatial resolution which has yet been obtained. At one extreme is the solar transition region, where only a very small fraction of the observed emitting volume is actually filled with plasma.

An estimate for the electron density can be deduced from the absolute intensity of one emission line, if the relevant atomic parameters are known. However, this method depends on several assumptions and breaks down if any filamentary structure exists.

Techniques have been developed to determine electron density from spectral line intensity ratios for the same ion. These methods make no assumption about the size of the emitting volume or the element abundance value. They therefore provide a powerful and important diagnostic for the solar plasma. Spectral lines may be grouped into different categories according to the way in which they are produced. In the coronal model approximation the spectral line intensity is a function of N_e^2; however, for some transitions, the dependency on N_e is different. The atomic processes within each ion determine the way in which the spectral line intensities vary with N_e.

For example, Si X, formed at around 1.3×10^6 K, provides a useful electron density diagnostic with lines at 347.4 Å and 356.0 Å. The intensity ratio (356.0/347.4) varies with electron density as shown in figure 5.

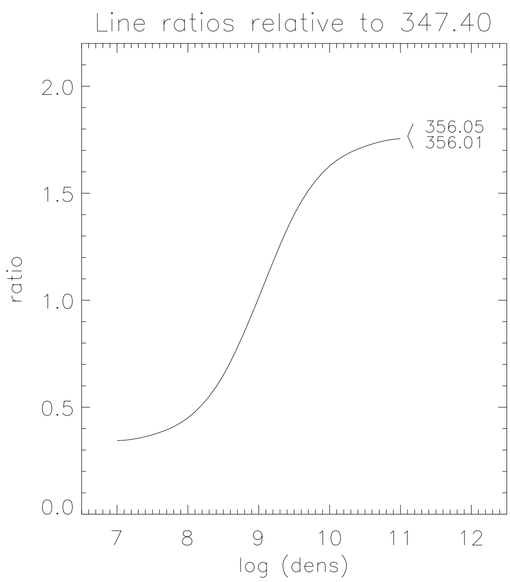

Figure 5. The Si X density sensitive 356.03/347.40 ratio (the observed 356.03 Å line is a blend of two Si X lines).

In the hottest parts of active regions the 356.0 Å line can be found to be around twice as intense as the 347.4 Å line, implying a high electron density $>10^{10}$ cm^{-3}. In contrast the characteristic electron density for the quiet Sun is around 10^8 cm^{-3} and in coronal holes it is even less.

Elemental composition

There has been a great deal of discussion and controversy about variations in the elemental abundances in the solar atmosphere (see SOLAR ABUNDANCES). The element abundances measured in the solar wind differ from those in the photosphere. The coronal abundances also differ from those in the photosphere, in fact they seem to vary in different solar features. This behavior depends on the value for the first ionization potential (FIP)—which is the energy required to ionize the neutral atom. The ions with FIP greater than 10 eV appear to behave differently from those with FIPs less than 10 eV. It is believed that this could reflect the ionization and acceleration processes for the solar corona, low down in the solar atmosphere.

The intensity of a spectral line is directly dependent on the elemental abundance. One approach to determining element abundances is to use the detailed shape of the emission measure distribution for ions from the same element and apply an iterative procedure to normalizing the curves for different elements. Another procedure is to use the intensity ratios for individual spectral lines which have very similar $G(T)$ functions, but different FIPs. For example, neutral neon, with an FIP of 21.6 eV, has a closed shell structure which is difficult to ionize, whereas it is much easier to ionize magnesium, with an FIP of 7.6 eV. Studies of the Mg/Ne relative abundances indicate that some low-lying dense structures in active regions have photospheric abundances, whilst other larger more open-loop structures have coronal abundances. This could indicate the emergence and heating of dense flux tubes from beneath the solar suface.

Elemental abundance determinations in a CORONAL STREAMER have recently been made with the Ultraviolet Coronagraph Spectrometer (UVSP) on SOHO. The UVSP team find a depletion of the high-FIP elements in the center of a quiescent streamer and suggest that gravitational settling may be partly responsible. It is important to attempt to relate the elemental abundances determined in the solar atmosphere with those measured further out in the solar wind.

Spectral line profiles

Line shifts and broadenings give information about the dynamic nature of the solar atmosphere. The transition region lines, formed at around 10^5 K, are characterized by broadened and irregular line profiles, which put constraints on possible heating processes. These profiles show evidence for small explosive events which occur around the edges of the magnetic network. They could be linked to coronal heating processes in the quiet Sun. Transient brightenings in transition region lines, called *blinkers*, have been observed by SOHO-CDS.

Many detailed studies have been carried out for a variety of solar features. For example, figure 6 shows a macrospicule-like feature at the limb, which was recorded by SOHO-CDS (Pike and Mason 1998). The left-hand side shows the OV intensity raster and the right-hand side shows an OV velocity map. If an axis is defined through the center of the OV feature and extended above the limb from the footpoint region, the emission is apparently blueshifted (black) on one side of the axis and redshifted (white) on the other. It is likely that a combination of both rotating and accelerating plasma would explain these observations.

Outflows of coronal material have been correlated with CORONAL HOLES, the source of the fast SOLAR WIND. The excess broadening of the transition region and coronal lines could be due to macroturbulence and provides valuable information on the heating of the solar atmosphere and the SOLAR WIND ACCELERATION.

The SOHO-UVCS instrument is designed to carry out diagnostic studies of the extended corona, in particular to measure coronal line intensities and profiles. For the O VI lines, a process called Doppler dimming enables a determination to be made of the solar wind outflow velocity. In the equatorial streamers, the outflow velocity reaches a value of around 100 km s^{-1} at four solar radii. Bright ray-like structures have been observed in coronal holes which could be related to POLAR PLUMES. The SOHO-LASCO (Large Angle Spectroscopic Coronagraph) instrument comprises three coronagraphs which cover different distances out into the extended corona. The inner coronagraph has the capability of observing in the green, red and yellow lines as well as in white light. Dynamic features can be tracked from close to the solar surface right out to 30 solar radii. In particular LASCO has observed many CMEs (coronal mass ejections), streamers, polar plumes and comets.

Conclusion

Spectroscopy provides a powerful opportunity for probing the nature of the solar atmosphere. This is illustrated by recent advances in UV observations of the transition region and corona by SOHO. In particular, examples have been given for diagnostic techniques involving optically thin emission lines. Lower down in the solar atmosphere (photosphere and chromosphere), it is necessary to solve the radiative transfer equations to study emission or absorption features.

The x-ray spectrum has only briefly been mentioned. The SOLAR MAXIMUM MISSION (SMM) satellite flown in the 1970s and the more recent YOHKOH satellite have provided extensive observations of active regions and solar flares in the x-ray wavelength range. A multitude of diagnostic possibilities exist and have been explored with these data.

From diagnostic studies of the solar atmosphere, we now know that the transition region is dynamic and filamentary in nature. MAGNETIC RECONNECTION at the network boundaries is correlated with enhanced transition region emission, indicative of heating. The corona is confined by small- and large-scale magnetic features. In active regions, the temperature is high and the measured

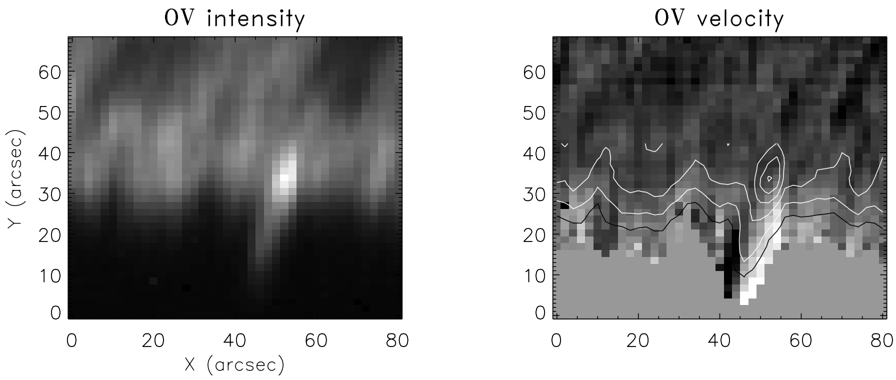

Figure 6. OV intensity (lhs) and velocity (rhs) maps for a solar tornado. The contours on the rhs velocity map are OV intensity. (From Pike and Mason 1998.)

electron densities are at least an order of magnitude higher than the quiet Sun. However, the densest, hottest parts of active regions are often low down, close to the regions of greatest magnetic shear. Large, cool (around 10^5 K) loops are a common feature of active regions. These are not stable and large velocities (around 100 km s^{-1}) have been recorded. In coronal holes, diagnostic studies give a low electron density and a characteristic temperature below 10^6 K. A heated debate is in progress about whether it is the polar plume or inter-plume regions which are the source of the high-speed solar wind. Initial velocity measurements from SUMER indicate that it is the latter, but further studies are in progress.

One has to stop and ponder what Newton would have thought about the advances which have been made in spectroscopy. Space technology has provided the opportunity to go far beyond the colors of the rainbow. Would he have shared our enthusiasm and excitement for studying the intricate features of the Sun?

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